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5e. TASK NUMBER

**5f. WORK UNIT NUMBER**

## 8. PERFORMING ORGANIZATION REPORT

Air Force Research Laboratory (AFMC)  
AFRL/PRS  
5 Pollux Drive  
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)	
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11. SPONSOR/MONITOR'S  
NUMBER(S)

Approved for public release; distribution unlimited.

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#### 14. ABSTRACT

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16. SECURITY CLASSIFICATION OF:

## 17. LIMITATION OF ABSTRACT

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19a. NAME OF RESPONSIBLE PERSON

Leilani Richardson

a. REPORT

b. ABSTRACT

c. THIS PAGE

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**Unclassified**

A

19b. TELEPHONE NUMBER

(include area code)  
(661) 275-5015

**Standard Form 298 (Rev. 8-98)**  
Prescribed by ANSI Std. Z39.18

Gifts enclosed!

⇒ Paper Rec'd After 30-day Deadline = 21 days until Deadline

FILE

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO)

21 August 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2002-207**  
Mike Fife (PRSS), "Electric Propulsion: An Introduction and Development Status" (viewgraphs only)

56792

VA Tech Grad Student Seminar  
(Blacksburg, VA, 09 September 2002) (Deadline: 09 Sept 02)

(Statement A)

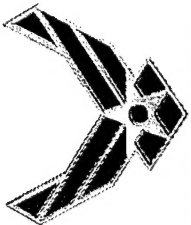
# **Electric Propulsion: An Introduction and Development Status**

**Virginia Polytechnic Institute**

**9 Sept, 2002**

**J. Michael Fife, Ph.D.**  
**Leader, Electric Propulsion Group**  
**Air Force Research Laboratory**





# Contents



- **AFRL/PRSS Laboratory Overview**
- **Fundamentals of Space Propulsion**
- **What is Electric Propulsion?**
- **Brief Description of Some EP Devices**
- **U.S. Government Hall Thruster Development**
- **Mission and Integration Issues**
- **Upcoming Air Force Missions Using EP**
- **Summary**

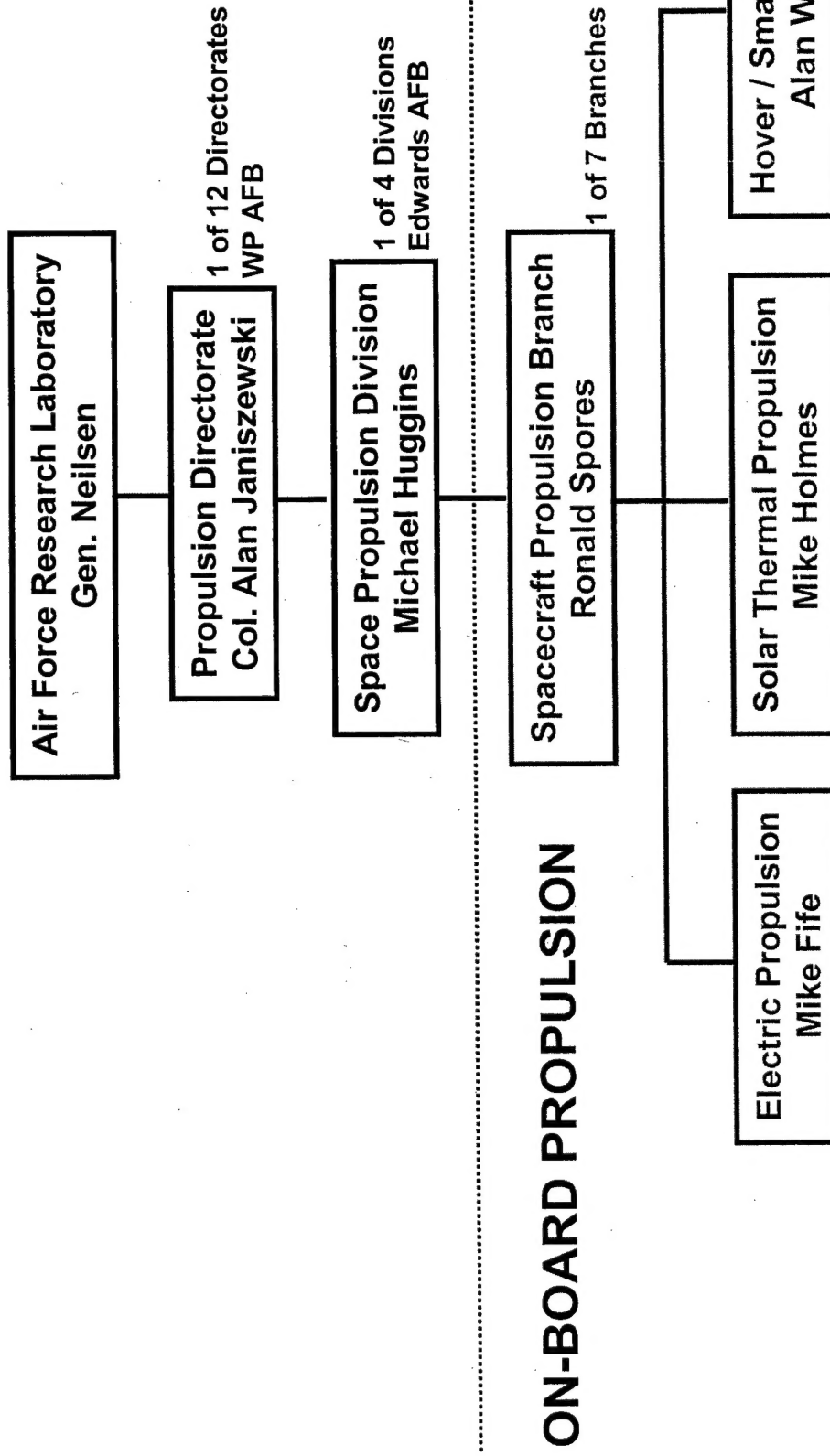




# AFRL EP Lab Overview

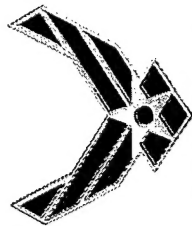


# Organization



## ON-BOARD PROPULSION

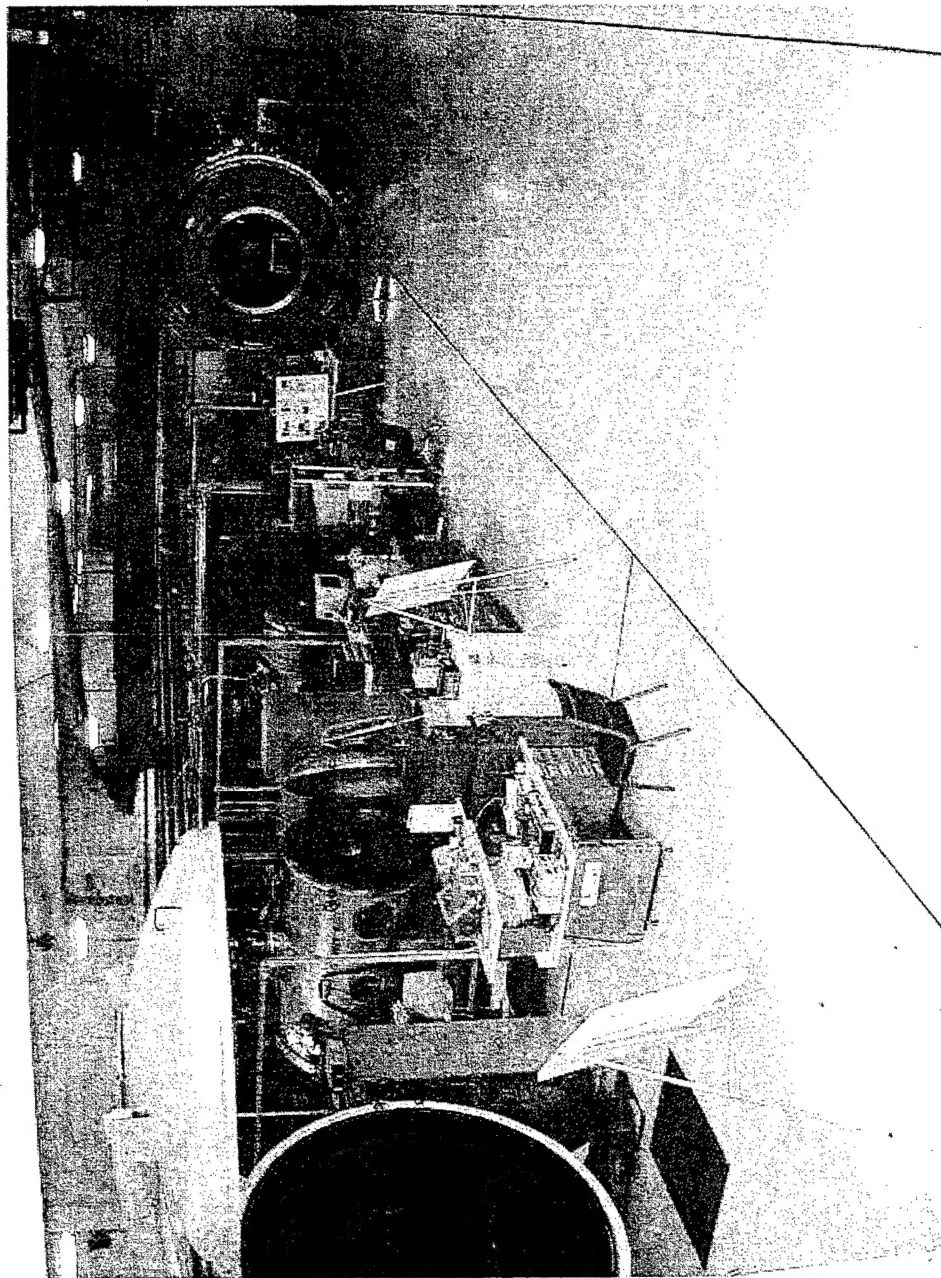
11 Government Personnel  
~20 Contractors



# AFRL Electric Propulsion Laboratory



Edwards AFB, CA



6 Vacuum Chambers

Full Time Personnel:

8 PhDs

3 Engineers

3 Technicians

1 Financial Analyst

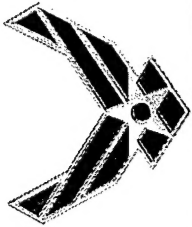
1 Admin. Assistant

Annual Budget:

~\$4M



# Fundamentals of Space Propulsion



# Fundamentals of Space Propulsion



$$F = ma$$

$$\dot{m}u = m\dot{v}$$



$$\frac{m_{0,P}}{m_0} = 1 - e^{\frac{-\Delta v}{u}}$$

Newton's Law

The Rocket Equation

$$I_{sp} = \frac{F}{\dot{m}g} = \frac{\dot{m}u}{\dot{m}g} = \frac{u}{g}$$

Specific Impulse

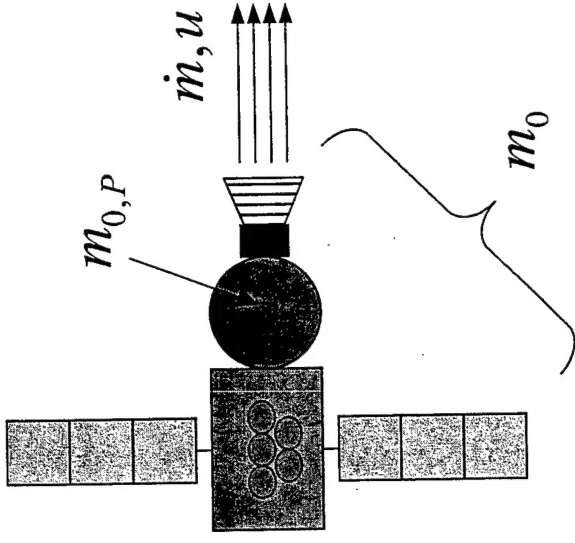
$I_{sp} \sim u$

$$\frac{m_{0,P}}{m_0} = 1 - e^{\frac{-\Delta v}{g I_{sp}}}$$

The Rocket Equation

**IMPORTANT RESULT:**

For fixed fuel fraction,  
 $\Delta V$  is proportional to  $I_{sp}$



$F \equiv$  Thrust

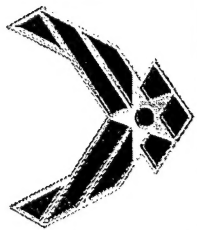
$u \equiv$  Propellant Velocity

$g \equiv$  Gravitational Constant

$\dot{m} \equiv$  Propellant Flow Rate

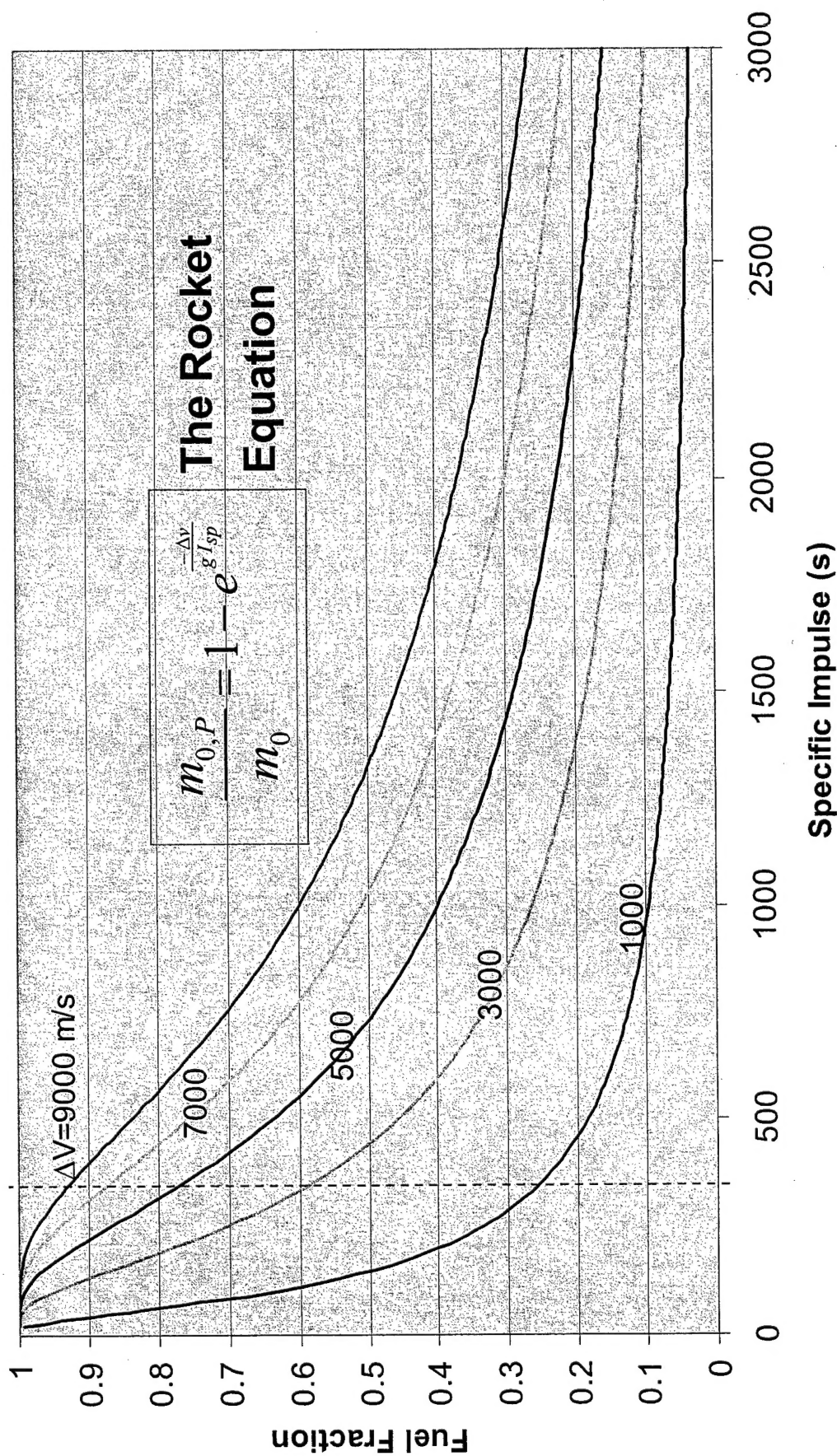
$m_0 \equiv$  Spacecraft Mass (initial)

$m_{0,P} \equiv$  Propellant Mass (initial)



# Fundamentals of Space Propulsion

BIPROP





# Benefits of Electric Propulsion



## Chemical Propulsion

$$E_{chem} = \frac{1}{2}mu^2$$

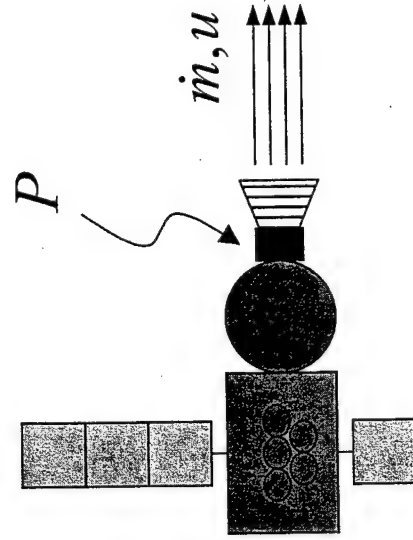
$$u = \sqrt{\frac{2E_{chem}}{m}}$$

$$I_{sp} = \frac{u}{g} = \frac{1}{g} \sqrt{\frac{2E_{chem}}{m}}$$

## General Propulsion

$$E = \frac{1}{2}mu^2$$

$$u = \sqrt{\frac{2E}{m}} = \sqrt{\frac{2P}{\dot{m}}}$$

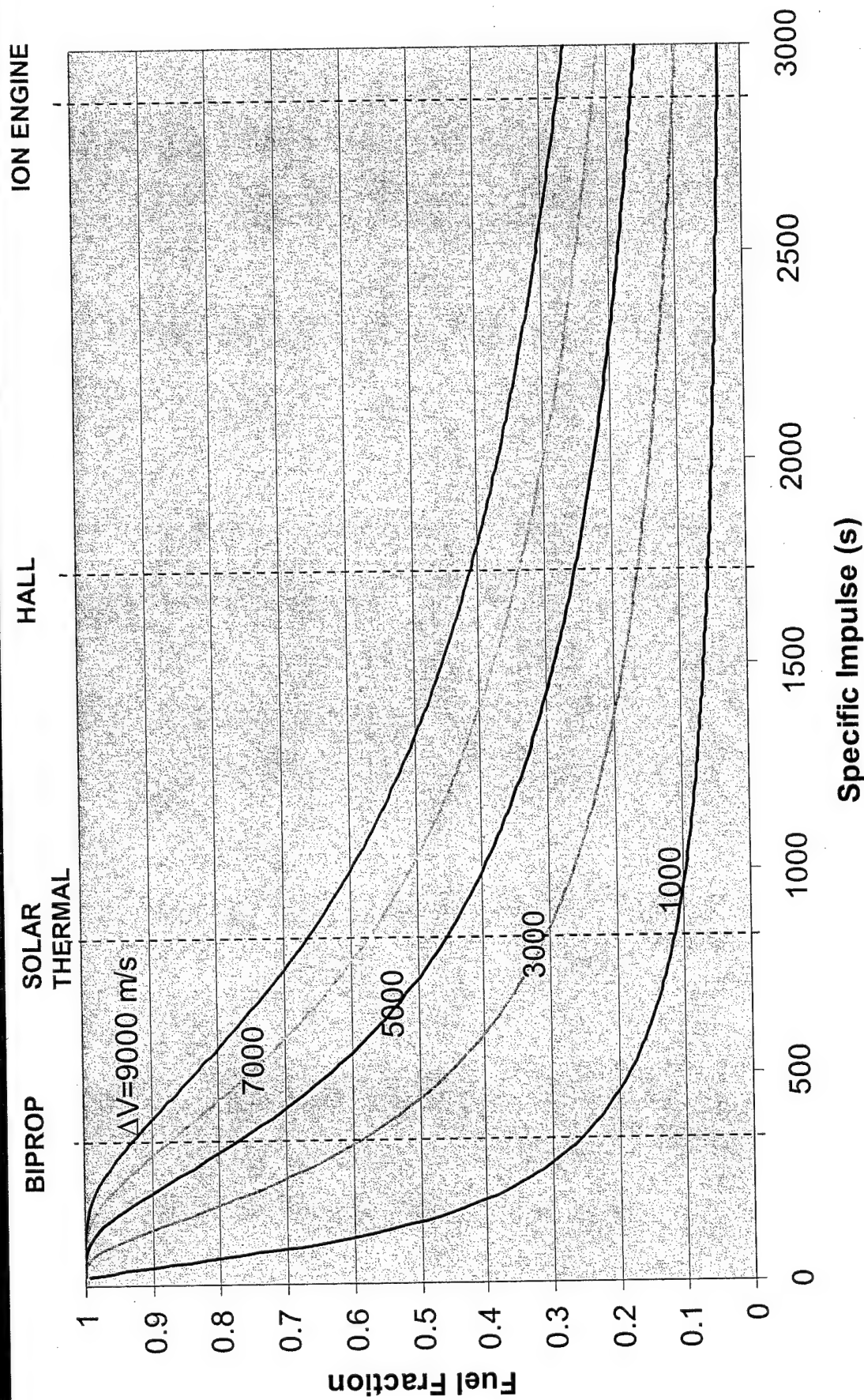


$$I_{sp} = \frac{u}{g} = \frac{1}{g} \sqrt{\frac{2P}{\dot{m}}}$$





# Benefits of Electric Propulsion





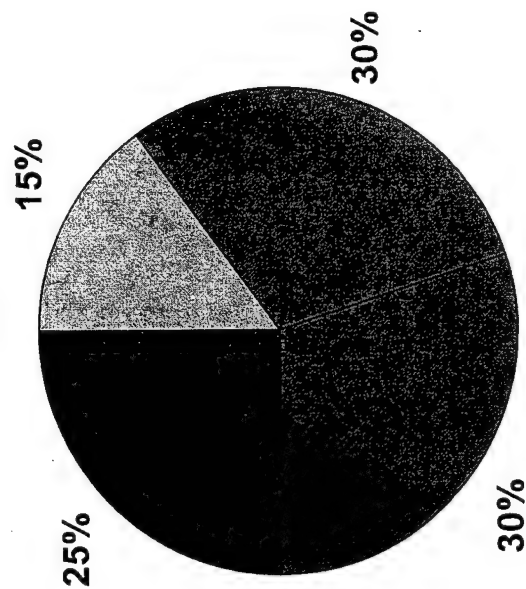


# Benefits of Electric Propulsion



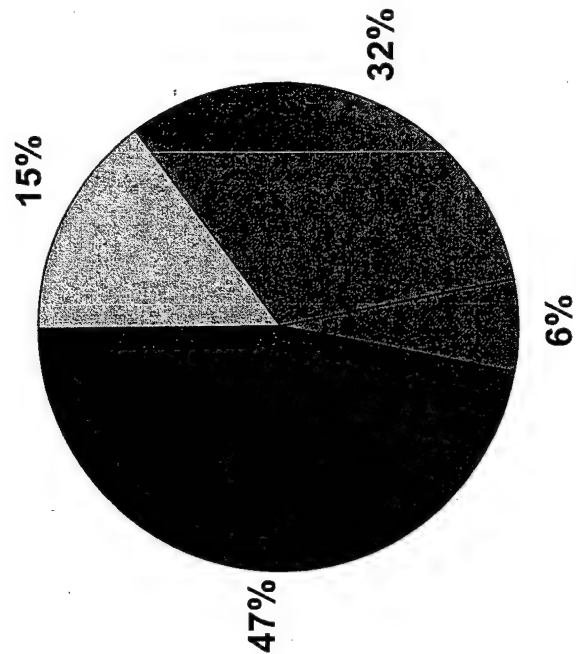
## Chemical

- Structure
- Bus
- Propellant
- Payload



## Electric

- Structure
- Bus
- Propellant
- Payload





# Electric Propulsion Power Limited



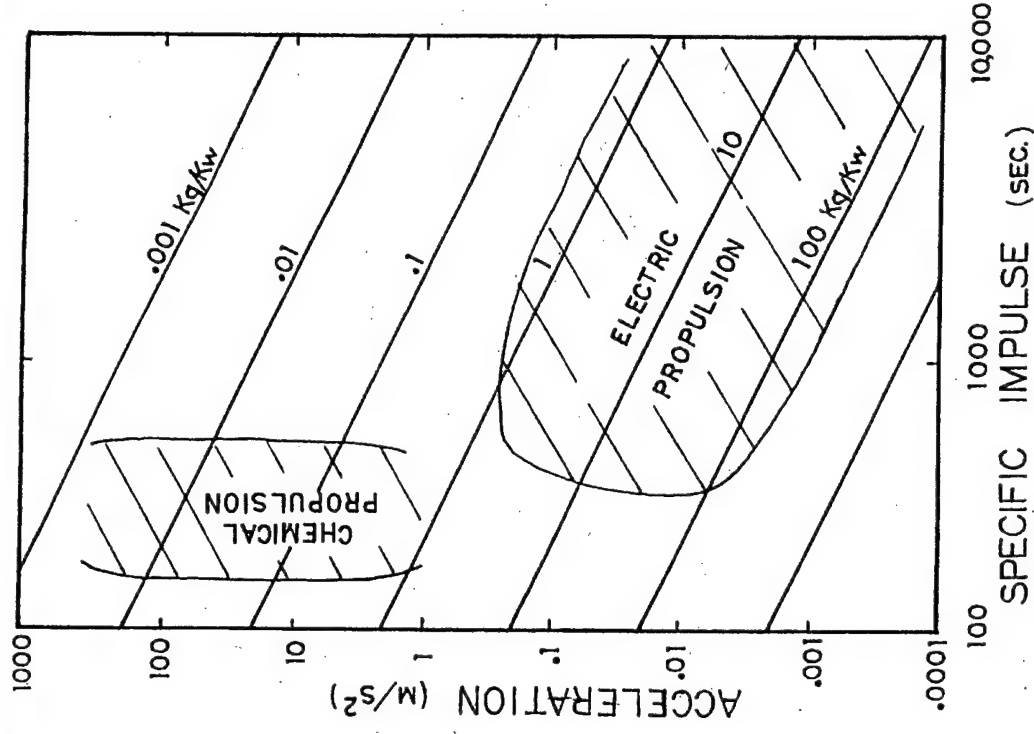
## JET POWER

$$P_{jet} = \frac{1}{2} \dot{m} u^2 = \frac{1}{2} (\dot{m} u) u = \frac{1}{2} F I_{sp} g$$

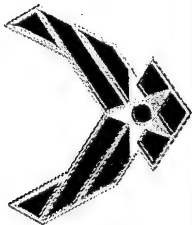
$$F = \frac{2P_{jet}}{I_{sp} g}$$



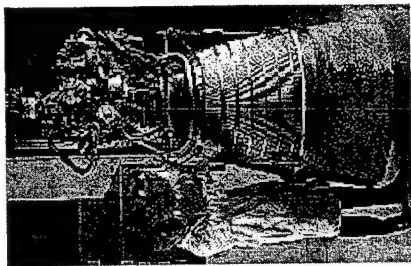
Low  $P_{jet}$ , High  $I_{sp}$  means  
**LOW THRUST**



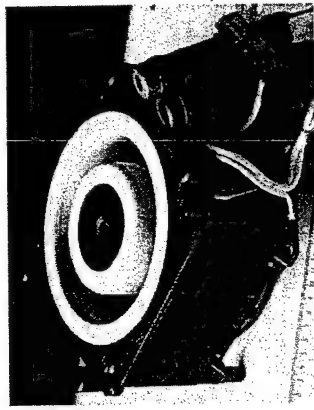
\*Prof. M. Martinez-Sanchez, M.I.T.



# Electric Propulsion Comparison with Chemical Propulsion



VS



Pratt and Whitney RL-10      Fake1 SPT-140 Hall Thruster

Propellant	LOX/LH2	Xenon
$I_{sp}$	410 sec	1800 sec
$P_{jet}$	134 MW	4.5 kW
F	66.7 kN	300 mN



# Electric Propulsion Low-Thrust Maneuver



Low-thrust EP requires non-Hohmann maneuvering

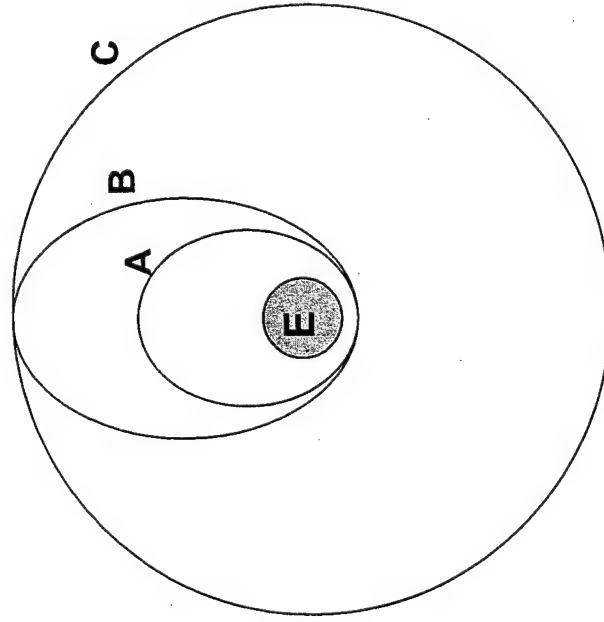
Example:

Orbit Raise of 10kW-class satellite

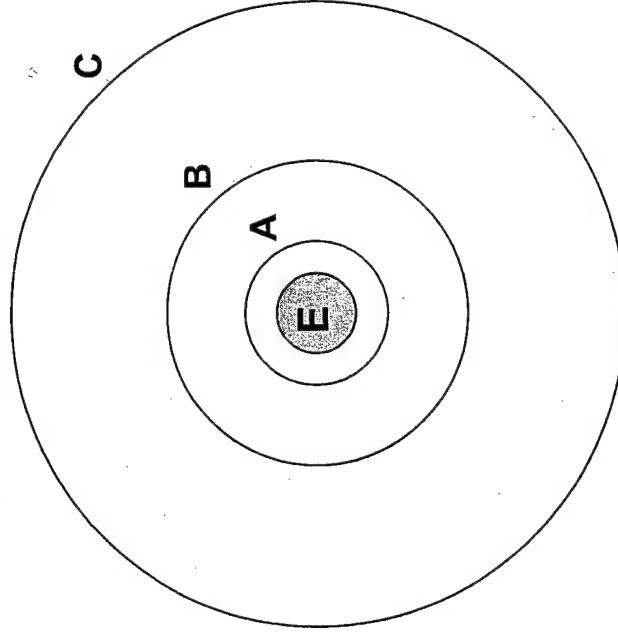
GTO-to-GEO

$F=300$  mN

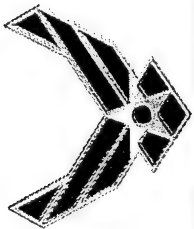
Trip Time: ~120 days



Partial-Period Apogee Boost



Continuous Thrust Spiral



# Electric Propulsion -- Review



## KEY EQUATIONS

$$\frac{m_{0,P}}{m_0} = 1 - e^{\frac{-\Delta v}{g I_{sp}}}$$

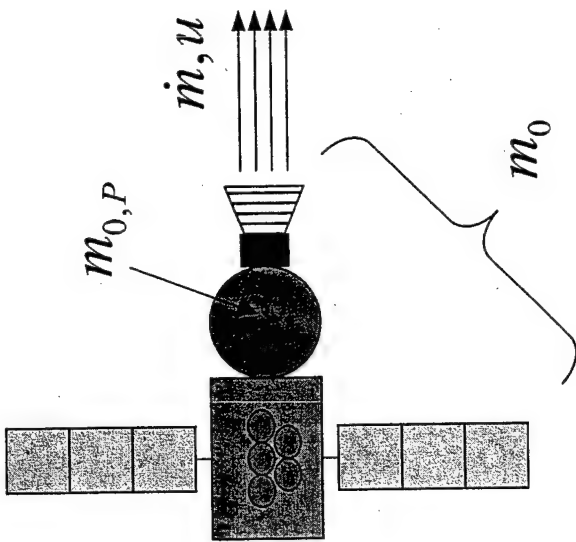
**ROCKET EQUATION --**  
Higher  $I_{sp}$  gives higher maneuverability with less propellant

$$I_{sp} = \frac{u}{g}$$

$I_{sp}$  is proportional to propellant exit velocity

$$F = \frac{2P_{jet}}{I_{sp} g}$$

Thrust is proportional to jet power, and inversely proportional to  $I_{sp}$



• EP devices can:

• GREATLY increase  $\Delta V$  (by over 5 times)

-or-

• GREATLY decrease propellant fraction

• EP devices have LOW THRUST, requiring long-duration firing

$F \equiv$  Thrust

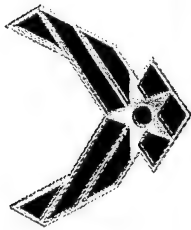
$u \equiv$  Propellant Velocity

$g \equiv$  Gravitational Constant

$\dot{m} \equiv$  Propellant Flow Rate

$m_0 \equiv$  Spacecraft Mass (initial)

$m_{0,P} \equiv$  Propellant Mass (initial)



# A Brief Description of Some EP Devices



# Typical Parameters of Small Thrusters



Thruster	$I_{sp}$ (s)	$\eta$	Thrust
Solid Rocket Motor	185	90+%	100+ N
Chemical Bipropellant	315	95+%	>2 N
Arcjets	~500 - 700s >1000 s ( $H_2$ )	~30%	0.1-1 N
Pulsed Plasma Thruster	200-1500	~15%	2 $\mu$ N – 4.5 mN
Colloid Thruster	450-1350	~50%	20 $\mu$ N
Hall Thruster	1500-3000	~50-60%	1.8–500 mN
Ion Thrusters	1700-3900 s	~65%	1-100 mN
Field Emission Thruster	6000-9000 s	~90%	40 $\mu$ N – 1.4 mN

Electric Propulsion Thrusters

blue = used as primary maneuvering engine

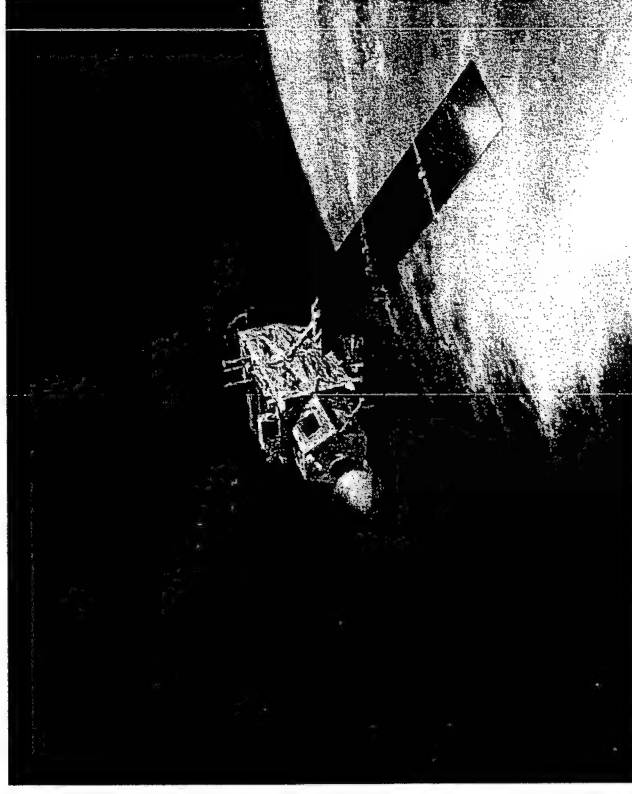
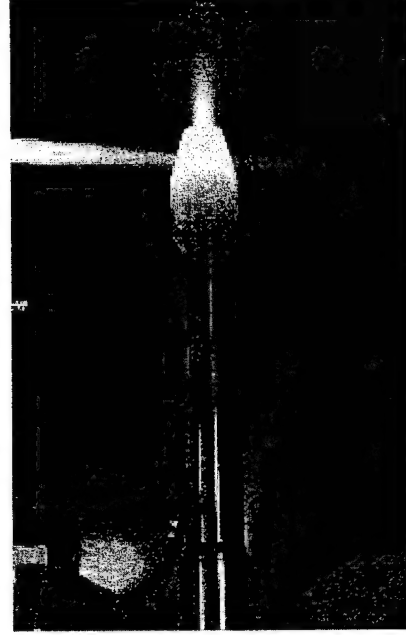
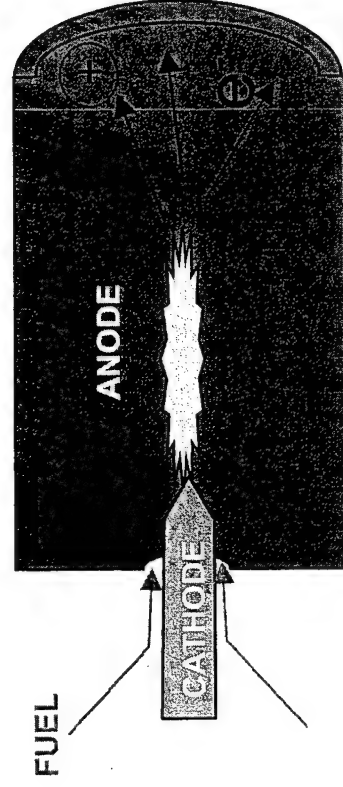


# Electrothermal Arcjets



- Principle: High translational energies through efficient heating

- Propellant:  $N_2/H_2$ ,  $N_2H_4$ ,  $H_2$



**ESEX 30kW ammonia arcjet**  
**Air Force flight experiment**  
**Flew successfully in 1999**

$I_{sp} = 500-1200 \text{ sec}$   
 $\eta = 20-30\%$   
Thrust = 0.1-1 N

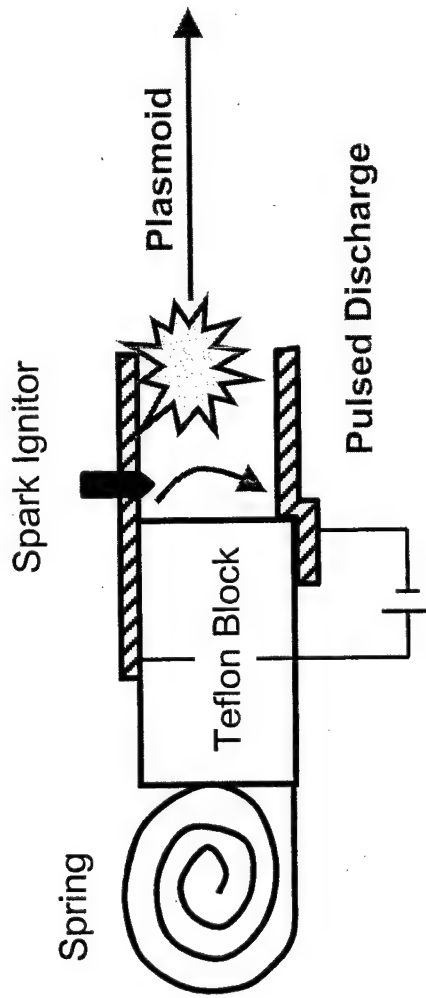




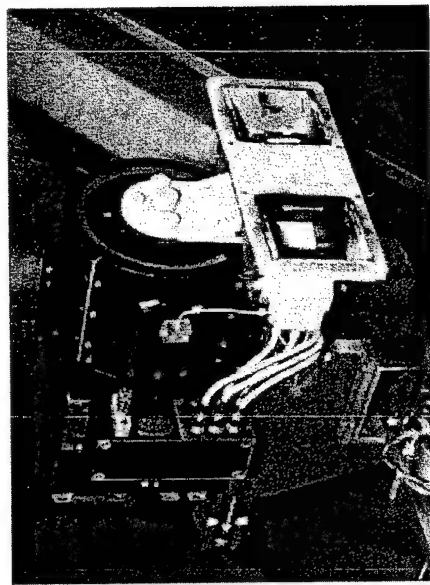
# Pulsed Plasma Thruster (PPT)



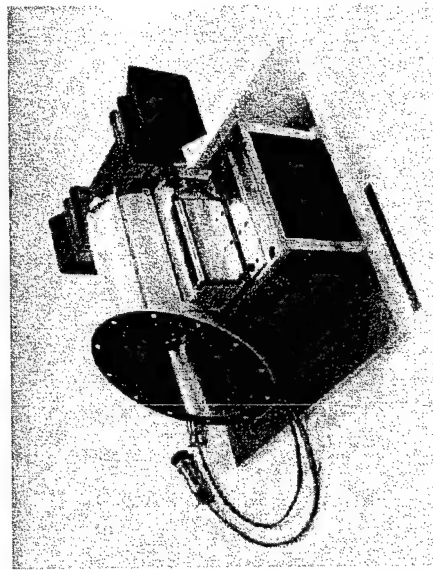
- Principle: Plasma Surface Ablation + Acceleration
- Propellant: Teflon, Teflon derivatives



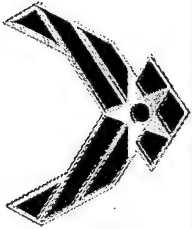
$I_{sp} = 200 - 1500 \text{ sec}$   
 $\eta = \sim 15\%$   
Thrust = 2 uN - 4 mN



LES 8/9



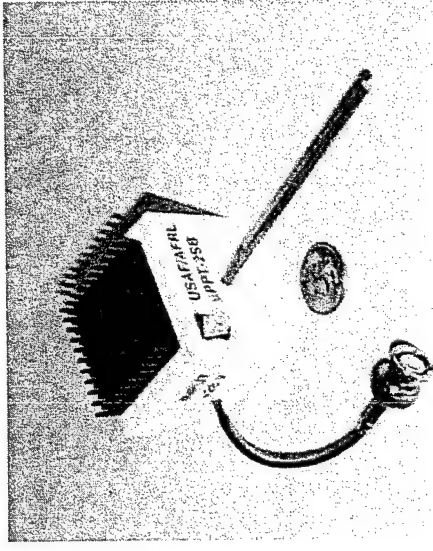
Primex EO-1



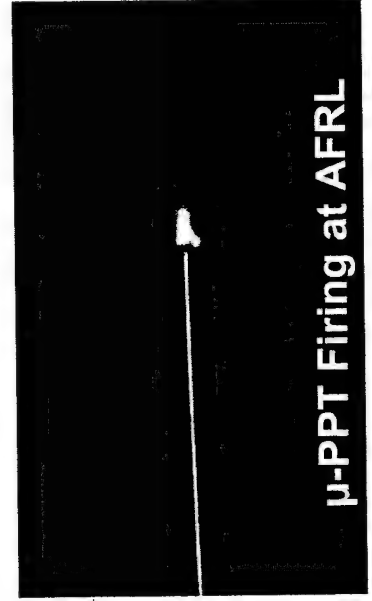
# Micro-PPTs



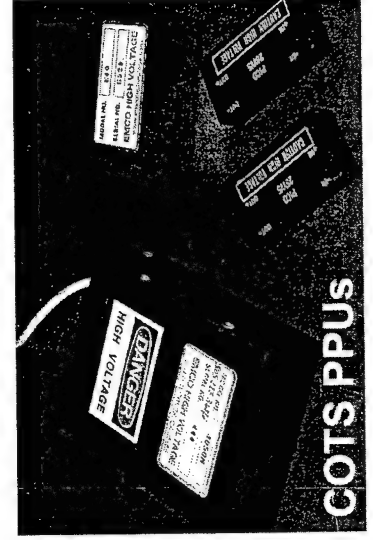
- Key development issues:
  - Thruster life as propellant recedes
  - Minimize operational voltage
  - Low mass power supplies and switching mechanisms
  - Quantify effluents
- Flight demo on TechSat 21



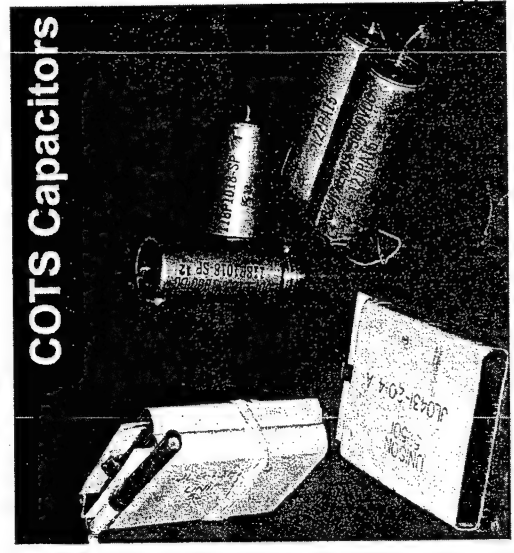
AFRL Patented Designs



$\mu$ -PPT Firing at AFRL



COTS PPUS



COTS Capacitors

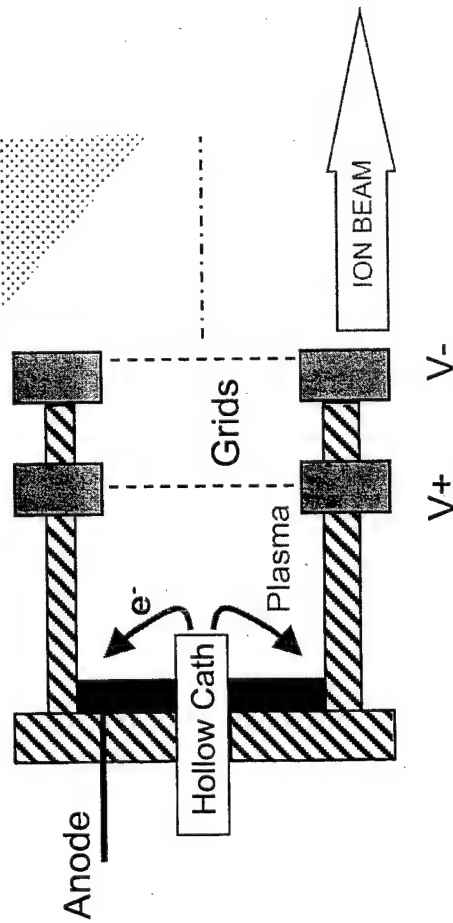


# Ion Engines

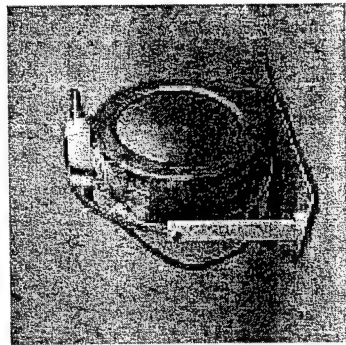


- Principle:  
Electrostatic Acceleration of Ions
- Propellant: Xe, Kr

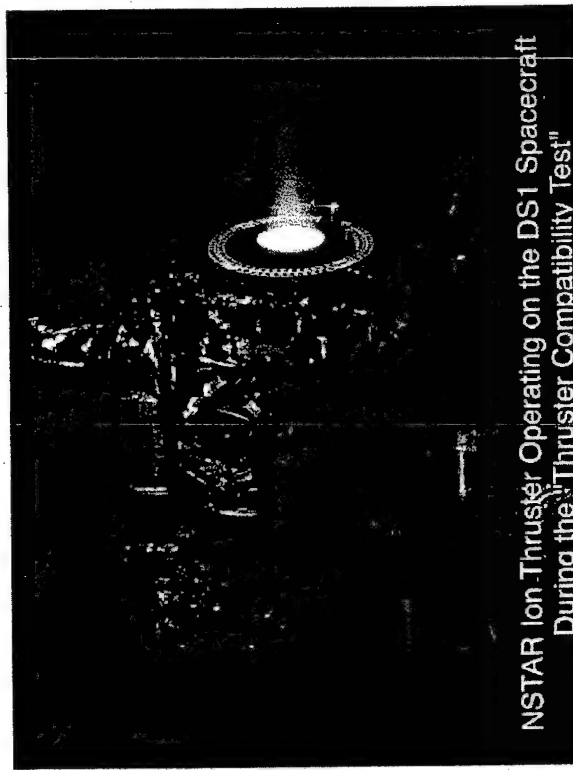
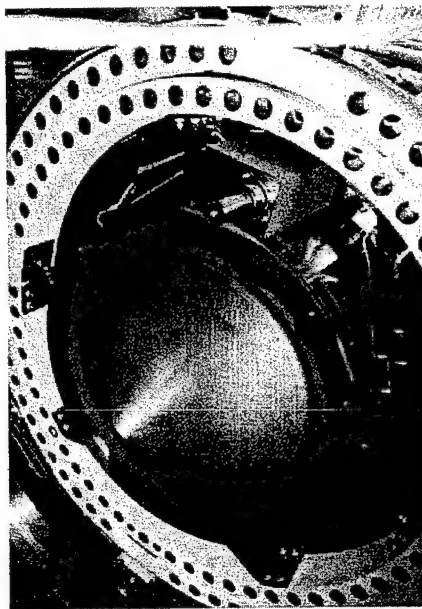
Hollow Cathode  
(neutralizer)



$I_{sp} = 1500-4000 \text{ sec}$   
 $\eta = \sim 65\%$   
 Thrust = 1-100 mN



NASA's NSTAR  
30cm Ion Engine



NSTAR Ion Thruster Operating on the DS1 Spacecraft  
During the "Thruster Compatibility Test"



# Hall Thruster

- Principle: Electromagnetic Acceleration of Ions
- Propellant: Xe, Kr

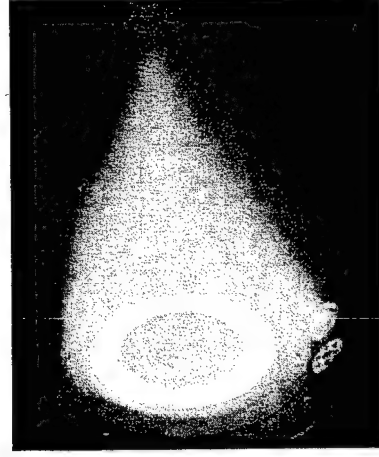
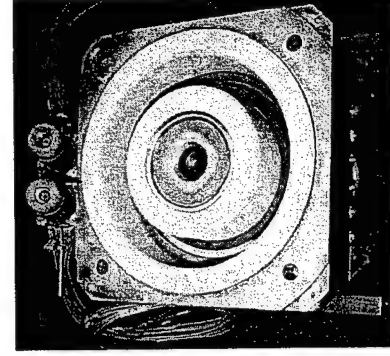
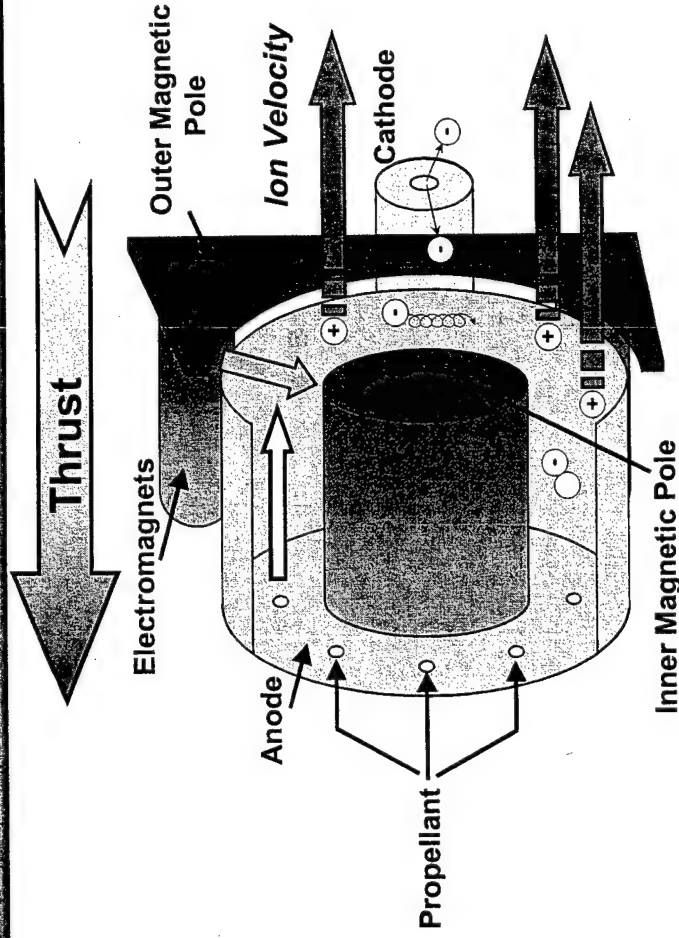
$I_{sp} = 1000-3000 \text{ sec}$

$\eta = 30-60\%$

Thrust = 5-400 mN

Power = 50W - 4.5 kW

1. Electrons emitted from the cathode travel toward the anode.
2. Electrons are impeded in the discharge channel by a strong radial magnetic field, causing a strong axial electric field to concentrate in this region.
4. This electric field heats the electrons, which subsequently ionize gaseous propellant (xenon) emitted near the anode.
6. The ionized gas accelerates axially through the electric field in the discharge channel, exiting the device at high speed, thus producing thrust.



Stationary Plasma Thruster (Fakel, Kaliningrad, Russia)

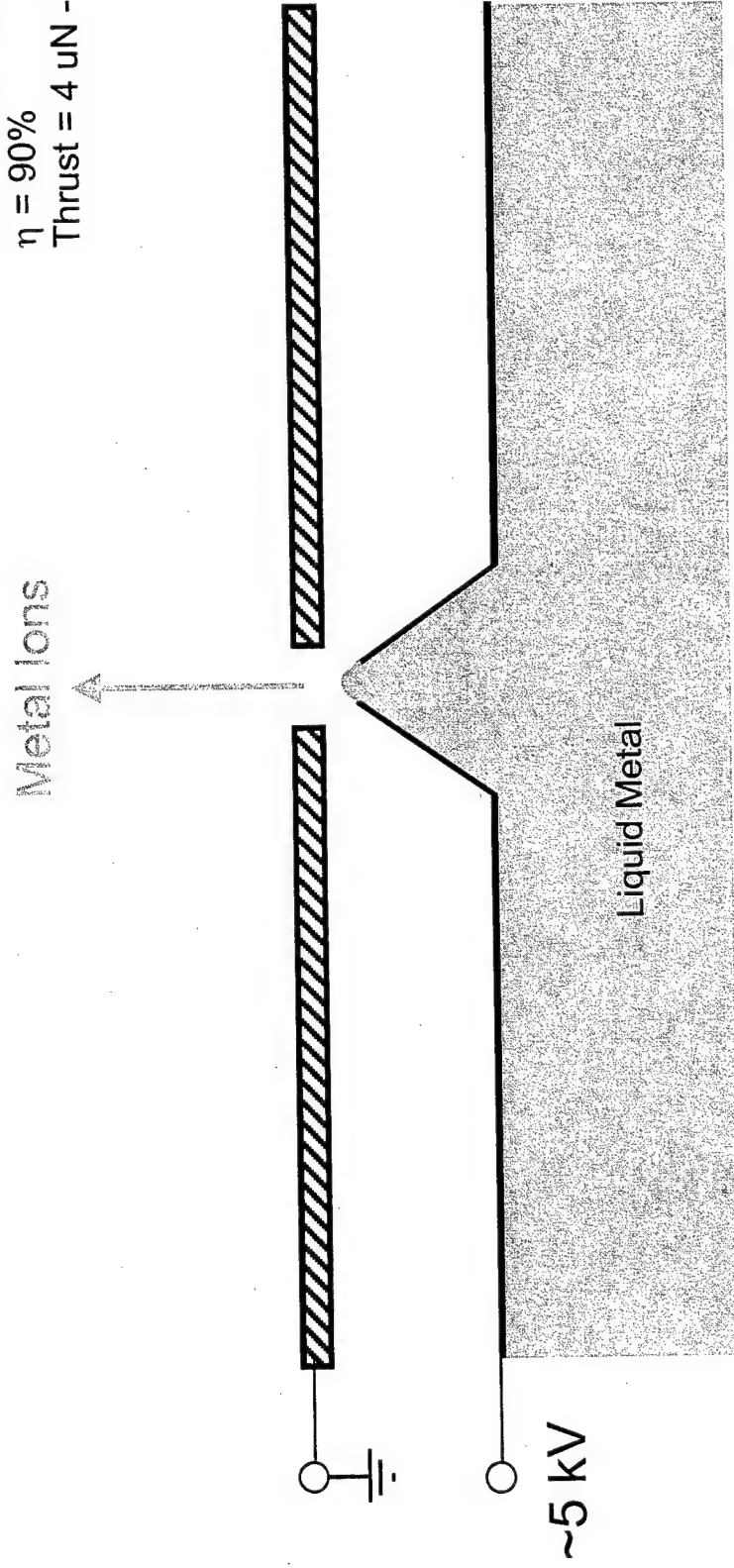


# Field-Emission Thrusters



- Principle: Field emission of ions from liquid metal
- Propellant: Cs, Ga, In

$I_{sp} = 6000-9000 \text{ sec}$   
 $\eta = 90\%$   
Thrust =  $4 \text{ uN} - 1 \text{ mN}$

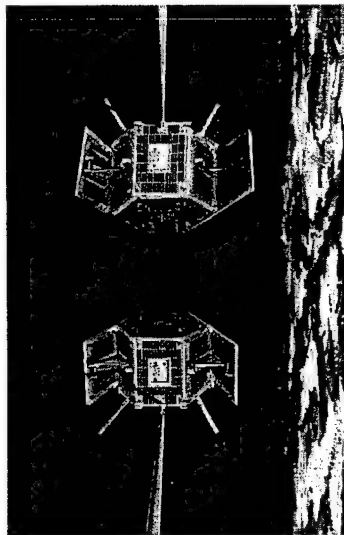




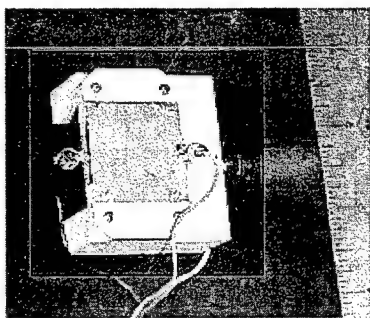
# Colloid Thrusters



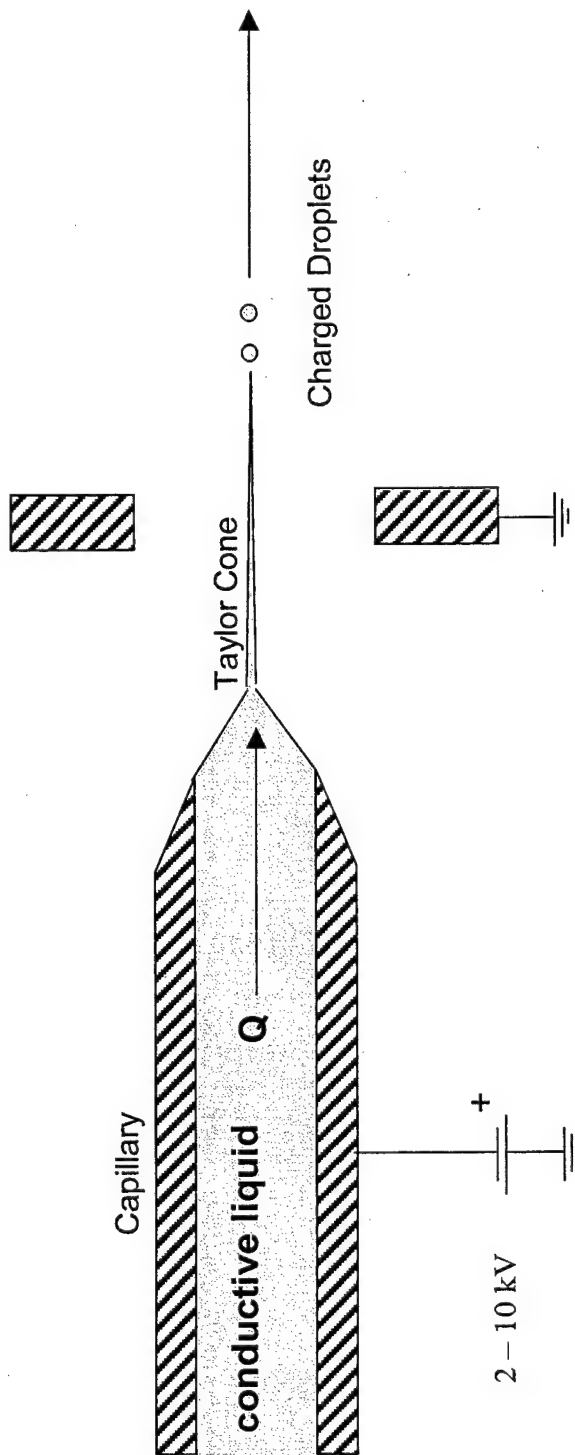
- Principle:  
Electrospray of charged droplets, ions
- Propellant:  
Electrolytes in viscous,  
low vapor pressure liquids

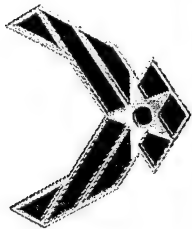


Stanford EMERALD PAIR  
AFOSR/DARPA Support



10 cm x 10 cm  
emitter array



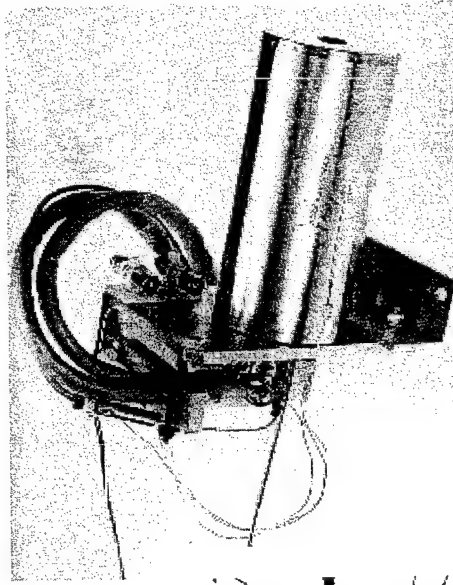
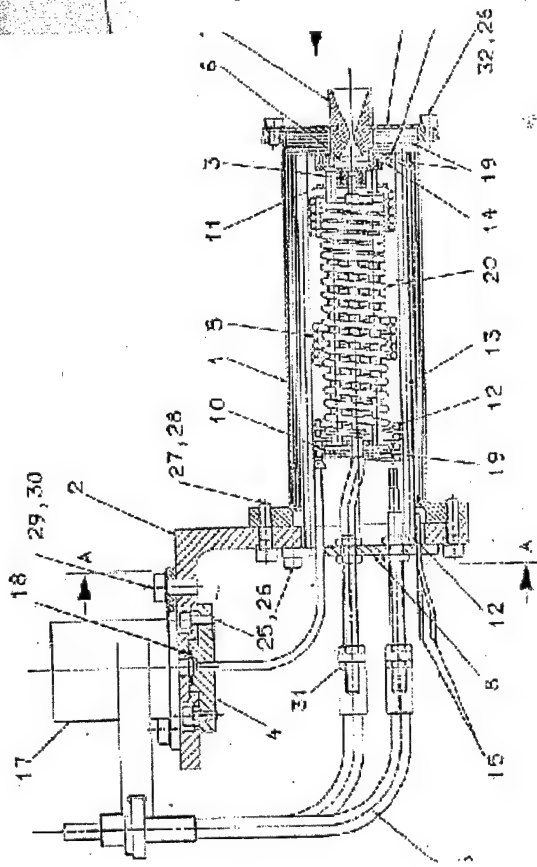


# “Other”



## Resistojet

Isp = 50-100 sec  
 $\eta = 10\%$   
 Thrust = ~10 mN

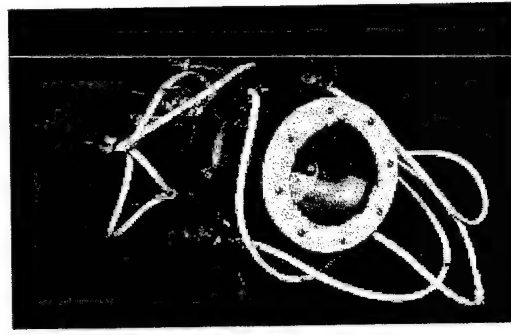
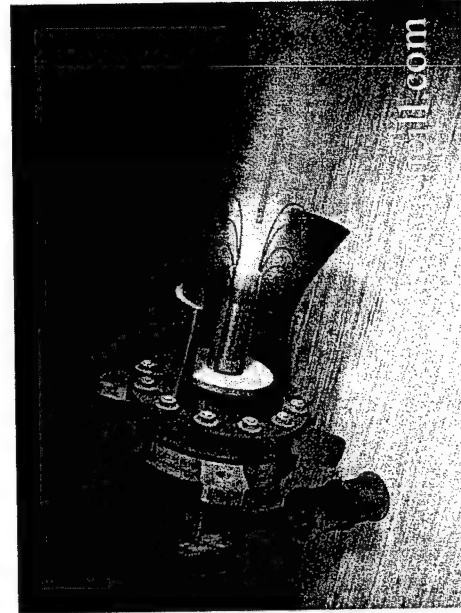


MBB ERNO

## Magnetoplasmadynamic (MPD)

### Thruster

Isp = ~4500 sec  
 $\eta = 30\%$   
 Thrust = ~1 N (Steady)  
 ~10 N (Pulsed)





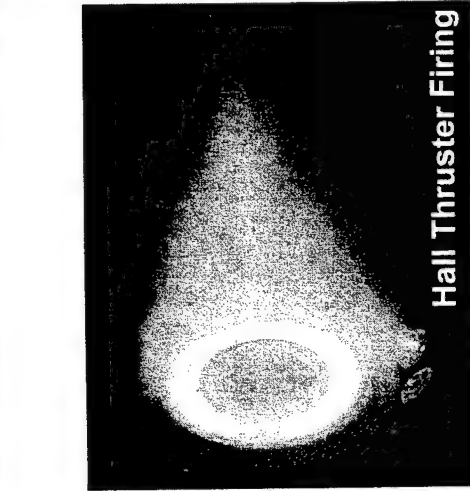


# U.S. Government Hall Thruster Programs

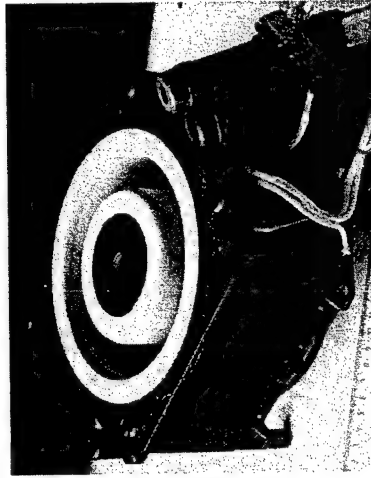




# Hall Thruster Technologies Under Development

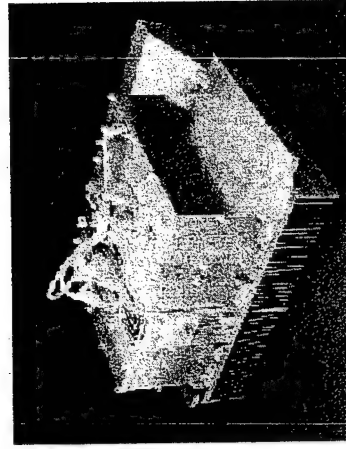
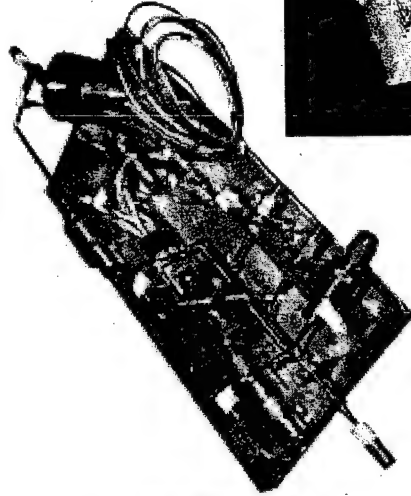


Hall Thruster Firing



Hall Thruster

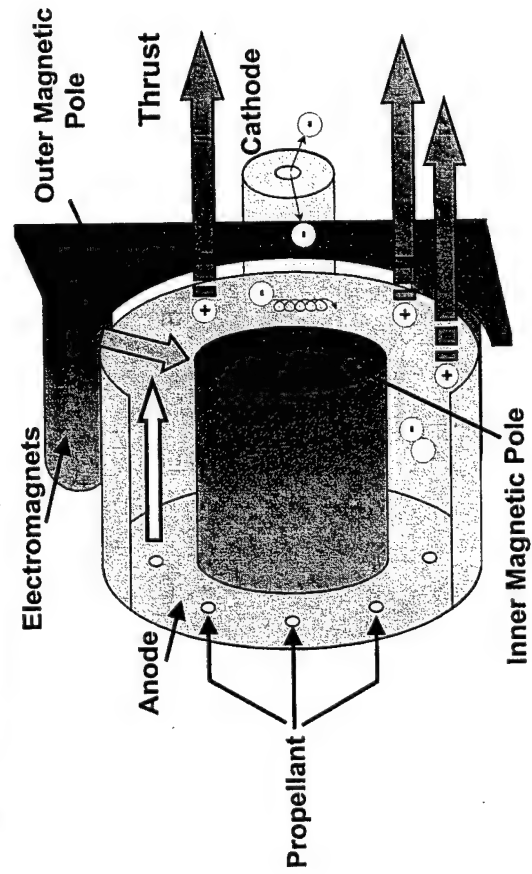
Propellant Management Assembly



Power Processing Unit



Cathode





# Programs Meeting IHPRPT Goals



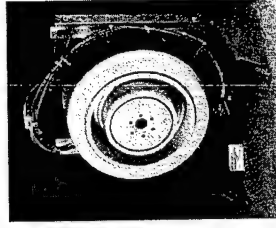
USAF – High Performance Hall System

Electrostatic Phase I



NASA – 10 kW T-220

Electrostatic Phase II



## IHPRPT OBJECTIVE STATUS:

### OBJECTIVE

### STATUS

$I_{sp}$  >1800 sec 1856 sec

Efficiency >51% 55%

Lifetime >7200 hours Begin Test Feb01

Specific Mass <6 kg/kW 5.7 kg/kW

- Exceeding all IHPRPT Phase I Objectives
- 22% increase in  $I_{tot} / M_{wet}$
- Program Completes in December 2002

## IHPRPT OBJECTIVE STATUS:

### OBJECTIVE

### STATUS

$I_{sp}$  >2000 sec 2500 sec

Efficiency >54% 61%

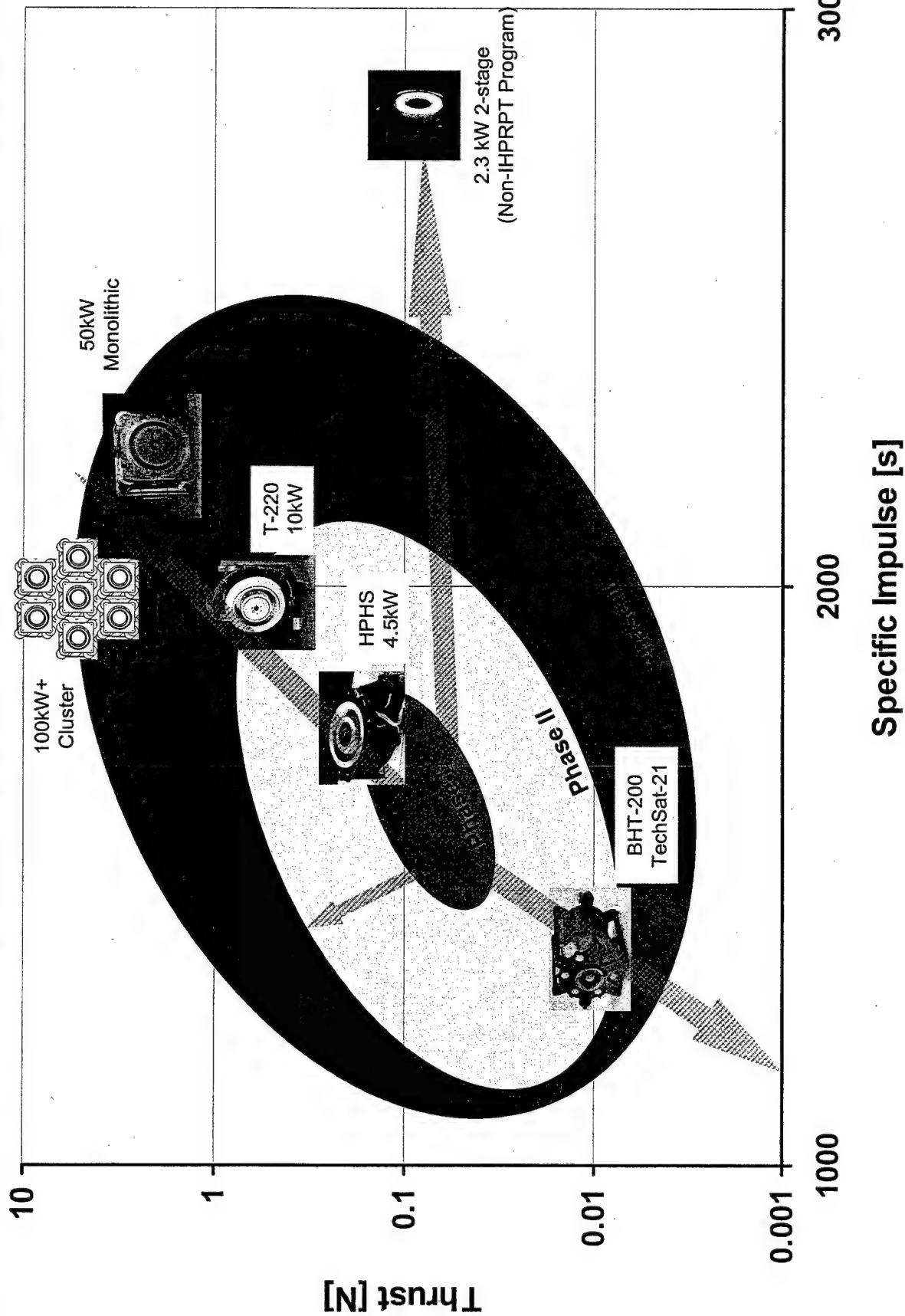
Lifetime >8000 hours Low Erosion After 1000 hour test

Specific Mass <2.7 kg/kW TBD

- Expected to meet IHPRPT Phase II Goal of 35% increase in  $I_{tot} / M_{wet}$

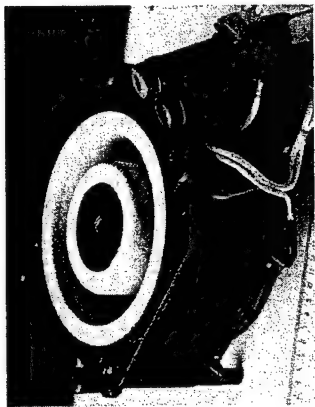


# Government Hall Thruster Programs





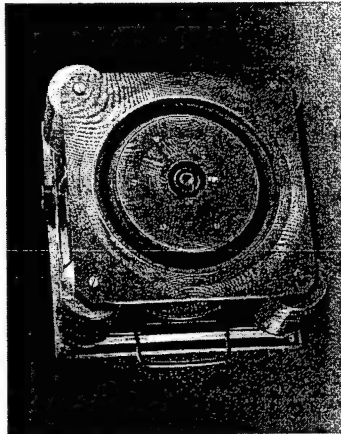
# Technology Development Cost



Stationkeeping/Orbit Topping



Small Sat Maneuvering

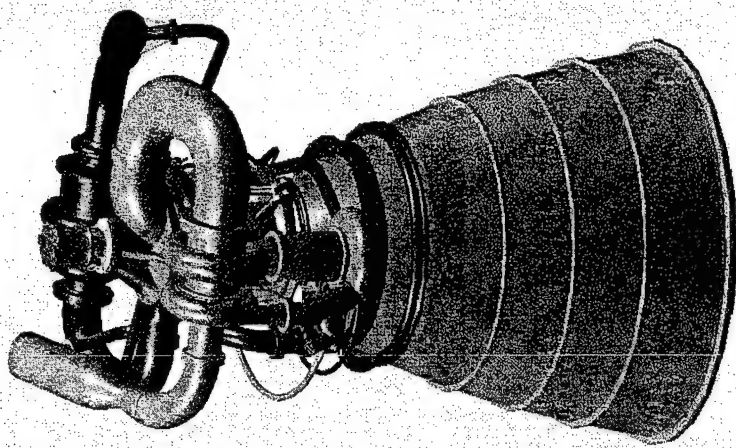


Orbit Transfer

**Hall Thrusters for  
Multiple Missions**

**\$17M**

**VS**



**Integrated  
Powerhead Demo**

**\$80M**



# 200W Hall Thrusters

## AFOSR/AFRL SBIR Funding



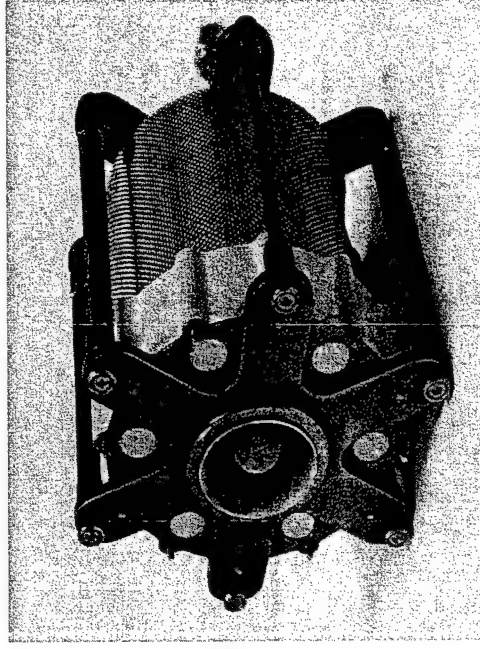
### Space Power Inc

- Thruster: AFOSR SBIR
  - PPU/PFS: BMDO SBIR
- (Managed by AFRL)



### Busek Co.

- Thruster: AFRL SBIR
- PPU: AFOSR STTR



- Both systems tested at AFRL, spring 2000
- Busek 200W Hall selected for USAF TechSat 21 flight demonstration
- Busek 200W delivered to MIT for plume measurements in preparation for MIT Hitchhiker on Shuttle



# 100W Hall Thrusters

Fakel, Tsnimash – EOARD Funding



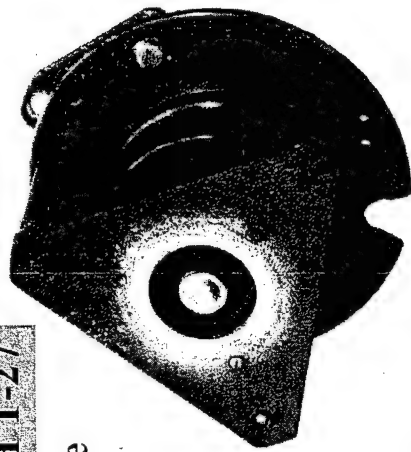
## TSNIIMASH T-27

Characterized performance

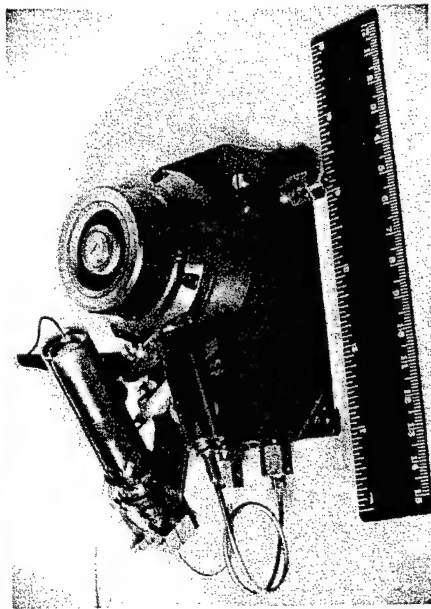
from 40 – 150W

Measure effects of varied:

- Power
- Propellant flow rate
- B field Strength



## FAKEL 100W Hall & Miniature Neutralizer

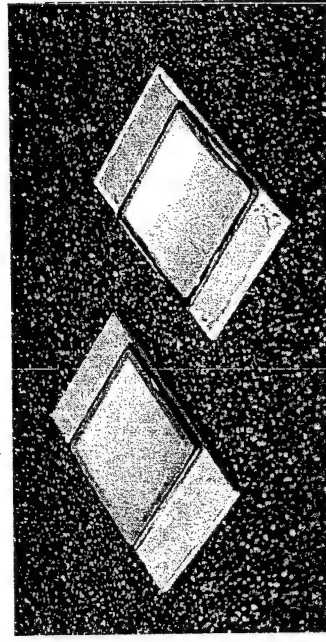
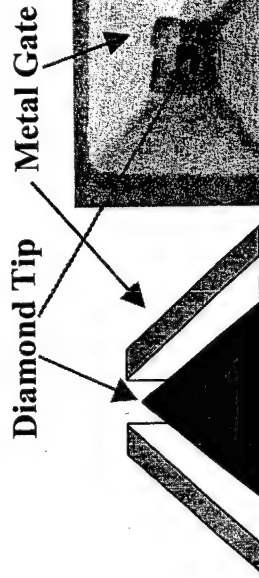


Power = 94.5 W  
Thrust = 4.7 mN  
Isp = 1000 s  
 $\eta = 24\%$  (incl. cathode)

Hardware delivered  
to AFRL

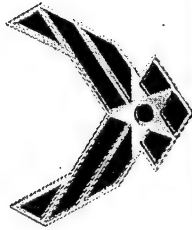
## Diamond Field-Emission Cathodes Busek – AFRL Phase II SBIR

- Low Power, No Propellant
- Characterization in progress



Each 1 cm<sup>2</sup> array has 100,000 Emitters





# Hall Thruster Cluster R&D

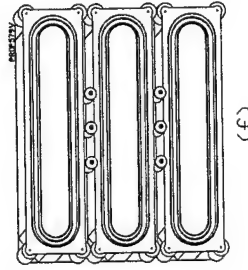
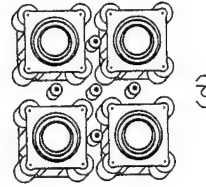
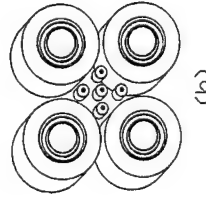
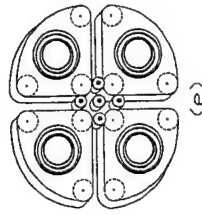
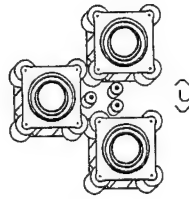
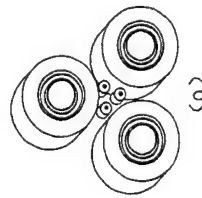
Busek & AFRL - AFRL Core and SBIR funding



**BUSEK**

Goal: Investigate cluster issues using small grouping of low-power Halls (~600W)  
- Enables cluster testing in smaller chambers

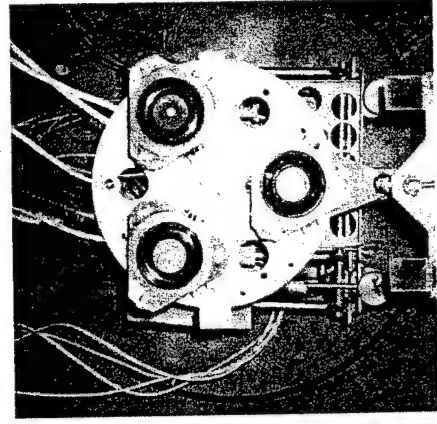
## Cluster options for R&D effort:



## Research Issues:

- Predict cluster S/C interaction using plume measurement from single thruster
- Determine degree of electrical cross-talk through plume plasma
- Determine optimal geometry
- Investigate neutralization techniques

## COMPLEMENTARY PROGRAM:



AFOSR/AFRL-Sponsored Hall Cluster Research at TsNIIMASH

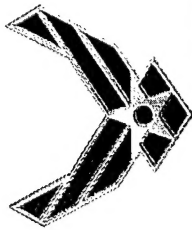
## Primary Goal for FY01:

- Identify critical issues requiring Basic Research
- Fire cluster at AFRL and characterize performance and behavior



# Mission and Integration Issues

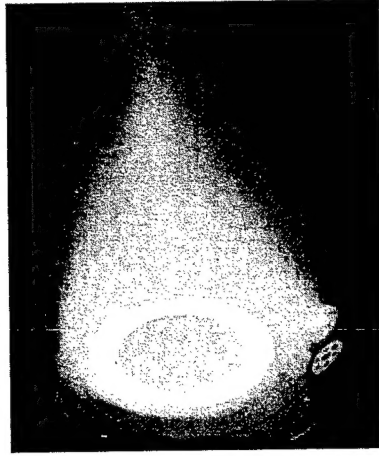
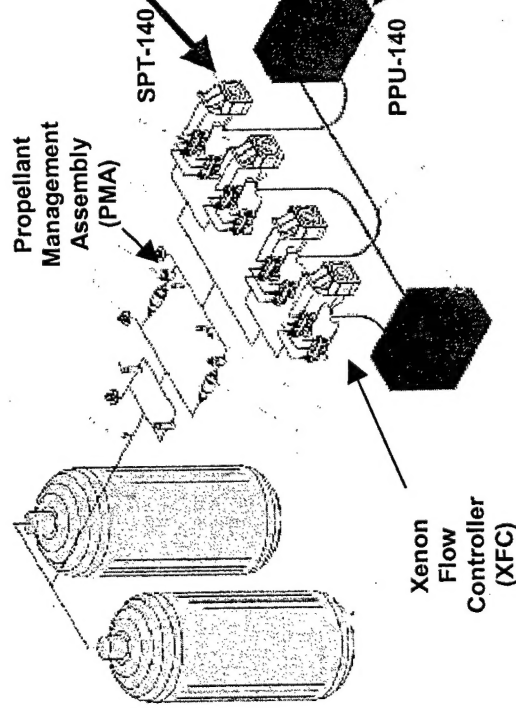




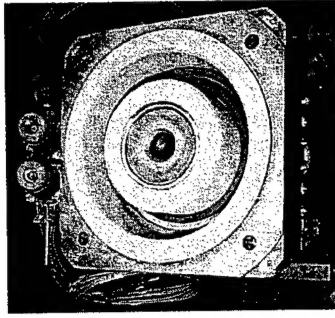
# Hall Thruster Integration Hardware



## Hall Propulsion System



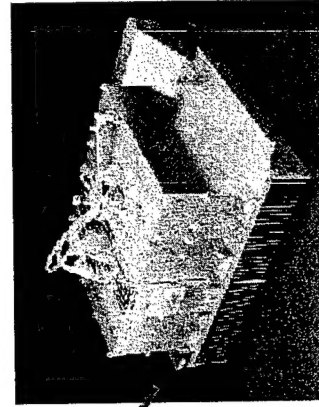
SPT-140 DM-3



SPT-140



PPU-140



PPU-140 Brassboard



# EP Thruster-S/C Interactions



EP Engines Emit High-Energy Particles

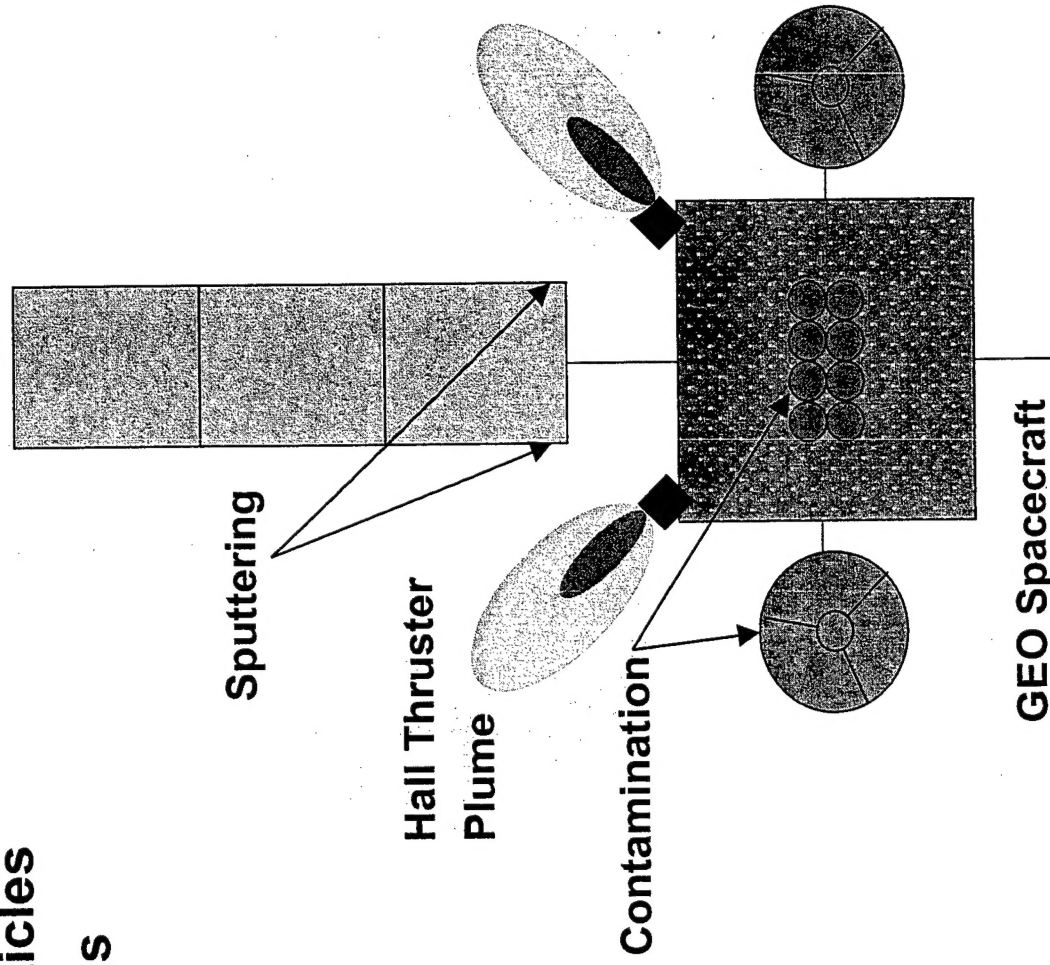
Hall/Ion Engine: ~300eV Xenon Ions

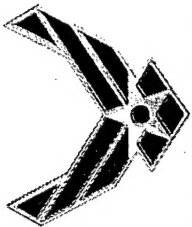
## Need to Predict:

- Contamination and Sputtering of Spacecraft Surfaces
- Solar Arrays
- Radiators
- Sensors
- Optics
- Cross-Contamination (S/C Clusters)
- Electromagnetic Interference
- Spacecraft Charging
- Observability

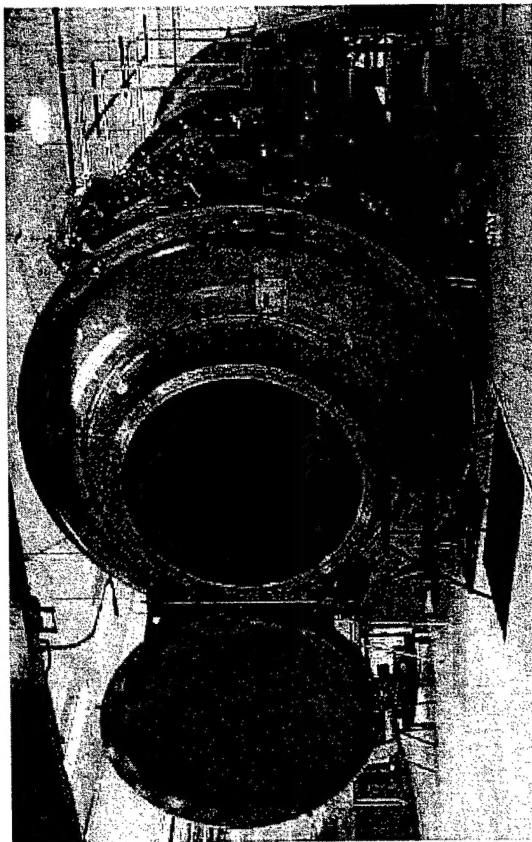
## Approach:

1. Ground and Flight Testing
2. Modeling and Simulation

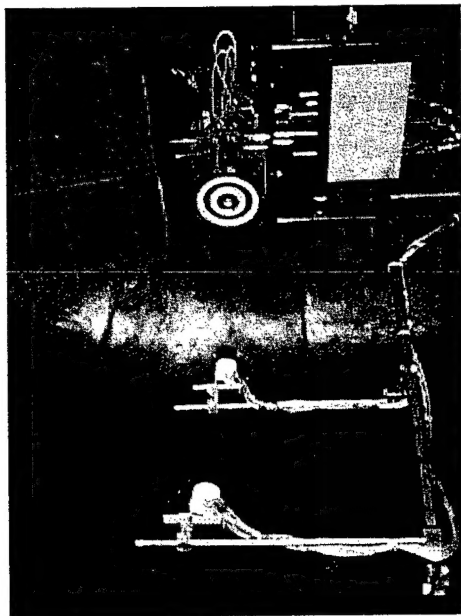




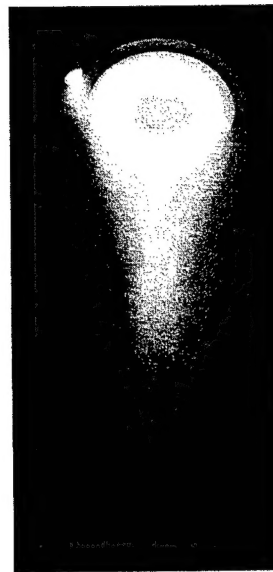
# EP Risk Reduction Testing and Modeling



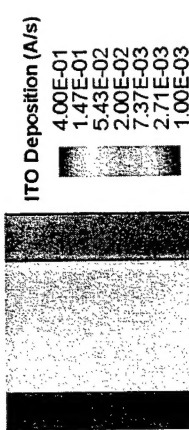
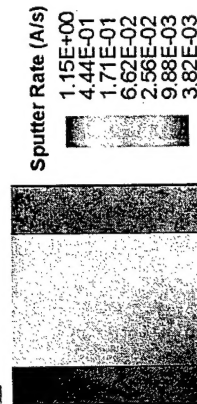
AFRL Hall Thruster Life Test Facility



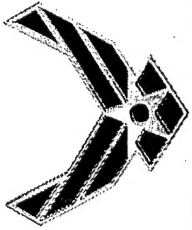
SPT-140 During Plume Divergence Testing



SPT-140 During Performance Eval



Modeling and Simulation of Thruster-Spacecraft Interaction



# Summary



- **Electric Propulsion (EP):**
  - Decreases spacecraft fuel fraction
  - Increases spacecraft capability
  - Enables new missions
- **USAF has selected Hall thrusters for intensive development due to optimum  $I_{sp}$  for many AF missions.**
- **Integration issues are a concern, and the focus of current research**